Because the dimensions of the cylindrical hole and wedge can be closely controlled and positioned on the resonator 24, and because the material properties of the parts are known and predictable, a precise deformation of the opening 28 can be achieved. The distortion must be symmetrically achieved if the forces in sidewalls 29 are to be kept equal. But if an offset compression is desired in order to potentially skew the axis along which the force of the piezoelectric element 22 acts relative to the resonator 24, then the hole 90 can be offset from the longitudinal axis 25.

Referring to Figures 12, the hole need not be circular, but could comprise a rectangular slot, with the wedge 92 being correspondingly configured to distort the hole 90 as needed to create the appropriate preload. A wedge 92 with a rectangularly shaped cross-section, or with an elliptically shaped cross section, could be used. As the shape of the wedge 92 changes to increase the amount of deformed material, the force needed to insert the wedge 92 into the hole 90 increases.

As discussed later, there are advantages in some situations if the piezoelectric element 22 applies its force along an axis either parallel to but offset from the longitudinal axis 25 of the resonator 24, or at a skew angle relative to that longitudinal axis 25. Figures 13-16 illustrate several ways to achieve this offset and skewing of the relative longitudinal axes of piezoelectric element 22 and resonator 24. Another variation is discussed later regarding Figure 53.

Figure 13 shows the piezoelectric element 22 offset within the opening 28 so the centerline 95 of the longitudinal axis of the piezoelectric element 22 is laterally offset from the centerline of the axis 25 of resonator 24. The offset can be above, below, or to either side of the centerline 25, depending on the desired motion of the selected contacting portion 44.

Figure 14 shows a small, hardened insert 94 interposed between one end of the piezoelectric element 22 and the adjacent wall of the opening 28. A hardened steel ball or a small disk could be used, but it must be sized or shaped relative to the abutting portions of the resonator so that no unacceptable deformation of the insert 94 occurs under driving forces applied by the piezoelectric element 22. In this embodiment a protective cap 34 is preferably used in order to avoid localized forces on the more brittle piezoelectric element 22 that might damage the piezoelectric. The location of the insert 94 can be above, below, or to either side of the centerline 25, depending on the desired motion of the selected contacting portion 44. More than one insert can be used.

Figure 15 shows the opening 28 and piezoelectric element 22 aligned along axis 95 of the piezoelectric element 22, but both located at a skew angle relative to longitudinal axis 25 of the resonator 24. This results in an asymmetrical mounting of the piezoelectric element 22 relative to the centerline of the resonator 24. The amount of skewing of the relative axes of the

The two vibratory elements 26 have axes 25 perpendicular to the longitudinal axis 45 of driven element 42, and on opposing sides of that axis 45. The selected contacting portion 44 of each vibratory element 26a, 26b is preferably intermediate the distal ends of the vibratory elements, but that need not be the case as the contacting portion 44 could be at distal end 36. The axes 25 of the vibratory elements 26 can be parallel and coplanar, but they do not have to be either parallel or coplanar. This arrangement lends itself to producing translation of the driven element 42 along its longitudinal axis 45, or rotation about that axis, or combinations of those motions.

Figure 28 shows two vibratory elements 26 resiliently urged against a common side of driven element 42. The two vibratory elements 26 have axes 25 perpendicular to the longitudinal axis 45 of driven element 42, but the axes 25 could be inclined to axis 45. The axes 25 of the vibratory elements 26 can be coplanar, but need not be so. The contact portions 44 are at distal edges of each face 36. The contact portion 44 is at an angle 45 degrees from the horizontal plane in which the axis 45 is shows as being located, but on opposing sides of that plane. This configuration lends itself to producing translation of the driven element 42 along its longitudinal axis 45, or rotation about that axis, or combinations of those motions.

Figure 29 shows a configuration similar to Figure 28 except that the vibratory elements 26 face each other and are located on opposing sides of the driven element 42 relative to the vertical axis.

Figure 30 shows a configuration similar to Figure 24, except there are two vibratory elements 26 on opposing sides of the driven element 26, on a common axis 25. The longitudinal axes 25 of each vibration element 26 need not coincide, but could be coplanar and skewed relative to each other.

Figure 31 has two vibratory elements 26 on opposing sides of the driven element 42, with the elements 26 facing each other but oriented at inclined angles α, β, respectively, relative to a plane through the longitudinal axis 45 of driven element 42. The angles α, β are shown so the axes 25 of each vibratory element 26 are parallel, but they need not be parallel. The angles preferably cause the longitudinal axes 25 to intersect the longitudinal axis 45 of the driven element 42, but need not do so. The selected contact portion 44 is at the distal end 36 of each vibratory element 26.

Figure 32 has two vibratory elements 26 on opposing sides of the driven element 42, with the elements 26 facing the same direction and oriented at inclined angles α, β, respectively, relative to a plane through the longitudinal axis 45 of driven element 42. The angles α, β are such that the longitudinal axes 25 preferably intersect longitudinal axis 45 of the driven element 42, but need not do so. The selected contact portion 44 is at the distal end 36 of each vibratory element 26.

and third vibratory elements, respectively. Figure 37 shows two vibratory elements 26a, 26b as described in Figure 27, each of which is resiliently urged against opposing sides of driven element 42. The two vibratory elements 26a, 26b each have axes 25 perpendicular to the longitudinal axis of driven element 42, and on opposing sides of that axis 45. The selected contacting portion 44a, 44b of each vibratory element 26a, 26b is preferably intermediate the distal ends of the vibratory elements, but that need not be the case as the contacting portion 44 could be at distal end 36. A third vibratory element 26c is located on an opposing side of the driven element 42 with its selected contacting portion 44c intermediate, and preferably equally between, the contacting portions 44a, 44b along an axis between 44a and 44b. The driven element 42 has its longitudinal axis along the z axial direction. Preferably, the first and second vibratory elements 26a, 26b contact the driven element 42 at the 12 and 6 o'clock positions, with the third vibratory element 26c contacting the driven element 42 at the 3 o'clock position. Other contact locations are possible. The contacting portion 44c is preferably at a distal edge of the vibratory element 26c, with the third vibratory element 26c being oriented at an angle α parallel to the plane containing axes 25a, 25b. The axes 25 of the vibratory elements 26a, 26b are preferably parallel and the axes 25a, 25b and 25c are preferably coplanar, but the various axes do not have to be either parallel or coplanar. This configuration provides for translation and rotation of the driven element 42 along and about its longitudinal axis 45, with the vibratory elements restraining translation in both directions along the y-axis, and in the +x direction, but allowing motion along the –x direction.

Figure 38 shows the vibratory elements 26 with their longitudinal axes 25 perpendicular to a radial axis extending in a plane orthogonal to the axis 45 of the driven element 42. The contacting portions 44 are illustrated as offset from distal ends 36, but that need not be the case. The vibrating elements 26 are shown as equally spaced with angles β, γ, and α each being about 60 degrees, but the angles can vary. The axes 25a, 25b, 25c are shown as coplanar, but they need not be so. The driven element 42 has its longitudinal axis along the z axial direction. This arrangement allows the vibrating elements 26 to restrain translation of the driven element 42 in both directions along the x-axis and y-axis.

Figure 39 places two of the vibratory elements 26a, 26b on one side of the driven element with axes 25a, 25b parallel to the x-axis, and with their respective contacting portions 44a, 44b engaging the peripheral portion of the driven element at corresponding locations along an axis parallel to the vertical y-axis. The contacting portions are located at edges of the distal ends 36a, 36b. The axes 25a, 25b are parallel and coplanar, but need not be coplanar or parallel. The third vibratory element 26c is on the opposing side of the driven element 42, with axis 25c parallel to the y-axis. The axis 25c is preferably coplanar with axes 25a, 25b, but need not be so. The

flexibility of the ring 110 helps to ensure that the vibration elements 26 are pressed against the driven element 42. As a result the rod is suspended at six points.

This configuration allows the vibratory elements 26 to support the driven element 42 so as to allow translation only along the longitudinal axis 45 of the driven element 42 and to allow rotation about that axis.

Motor Operating Principles

The following description helps understand the operation of the above-described embodiments, and helps understand the variety of ways to implement these embodiments and variations thereon.

The present motor uses only one piezoelectric element 22 with one electrical excitation signal to excite various modes of vibration of the vibration element 26. The motion of the contact portion 44 is determined by these modes of vibration. In particular, the present motor achieves an elliptical movement of the contact portion 44 in a first direction for a sinusoidal electrical excitation signal at a first frequency, and an elliptical movement of the contact portion 44 in a second direction for a sinusoidal excitation signal at a second frequency, providing a required force or amplitude of motion or speed at the contact portion 44. Elliptical movements of the contact portion 44 in a third and more directions for sinusoidal excitation signals at third and more frequencies are known to be possible.

The motor assembly 20 is advantageously configured so that the contact portion 44 traces the elliptical motion several tens of thousand times per second to make motor operation inaudible for humans and most pet animals. During a selected segment of each elliptical cycle, the contact portion 44 comes into contact with the engaging surface of the driven object 42 where it exerts a frictional contact force that transports the driven object 42 by a small amount into a corresponding direction. The observed macroscopic motion of the driven object 42 is the accumulation of all individual transportation steps.

While the bulk of this disclosure refers to a contact portion 44 located at a distal end 36 of vibration element 26 and moving in a first elliptical path 100a causing the driven object 42 to be transported in direction of the driven object's longitudinal axis 45, and the same selected contact portion 44 moving in a second elliptical path 100b causing transportation in an opposing direction (as in Figures 2 and 5), the first and second selected contacting portions 44 need not be the same, need not be adjacent, and need not be located at a distal end 36. They need only be located on the same vibratory element 26. Further, the number of selected contacting portions 44 and the directions and orientations of respective elliptical paths 100 at each contacting portion can vary according to the particular design. There could be three, or there could be more. There

usable amplitudes. Cross-sectional contraction is governed by the Poisson-effect. This effect is strongest where the longitudinal strains in the piezoelectric element 22 or resonator 24 motors are the highest, i.e., where the stresses are highest. Cross-sectional contraction can therefore be large where the piezoelectric element 22 is connected to the resonator or whatever frame is holding the piezoelectric element and the portion of that connection in which the forces are high. This contraction can drive the bending vibrations of the thin sidewalls 29 (Figure 1) of the resonator 24. If the bending resonant vibration modes of the sidewalls 29 are tuned to the longitudinal vibration mode of the vibratory element 26, yet another splitting of natural vibration frequencies can occur with similar benefits as mentioned above.

The piezoelectric element 22 generates predominantly longitudinal forces in the resonator 24 within which it is mounted. Coupling of these longitudinal forces from the vibratory element 26 into directions other than along longitudinal axis 25 creates a number of other possible vibration modes within the vibration element 26, such as bending, shear and torsion. The intensity of the coupling of the longitudinal motion with other vibratory motions within the vibratory element 26 can determine the relative amplitudes of the various modes of the vibratory element 26 and therefore their relative contributions to the motion of the selected contact portion 44. Coupling can be generated by material properties, geometric imperfections and asymmetries within the components of the vibratory element 26, primarily the piezoelectric 22 and the resonator 24.

Some of these coupling effects are often poorly defined, difficult to analyze, and hard to measure or design. Well-defined mechanisms are therefore preferable. These mechanisms include mounting the piezoelectric element 22 off-center of the longitudinal axis 25, or at an angle to the longitudinal axis 25 of the vibratory element 26, or using flexible mountings for the vibratory element 26 such as a spring 50 or similar elements. In the case of a spring 50, the longitudinal motion of the vibratory element 26 generates bending in the spring 50. The end 50b of the spring that is clamped to the vibratory element 26 is forced to bend or possibly to twist. This bending or twisting causes bending moments to be generated in the vibrational element 26. The configuration of the spring 40 could be used to vary the vibrational mode, as for example by introducing bends, edges and similar modifications into a flat metal spring. Furthermore, the spring 50 can be made more flexible at specified locations to better define an axis of rotation about the flexible portion, if that is useful to the design. Coupling of vibration modes within the vibratory element 26 can also be achieved if the piezoelectric element 25 is selected or configured or excited to perform other than pure longitudinal motions.

Several additional factors are preferably considered in configuring the vibratory element 26 and the motor 22. These factors include: the orientation of ellipse 100 in which the selected

Figure 66 shows a driver circuit suitable for use with a piezoelectric element 22 that may be more sensitive to a negative voltage. In this circuit, a second physical capacitor 154b is added to the piezoelectric element 22 (represented as capacitor 154a), or multiplayer piezoelectric element 22, if it has multiple piezoelectric layers that are electrically split as shown, can be represented as two capacitors 154a and 154b. Also, another resistor 156b is included in the circuit in addition to the existing resistor 156a. Parallel to the resistors 156 and the capacitors 154, two diodes 160a, 160b are added.

The orientation of the diode 156a prevents the voltage of the node between the two resistors 156a, 156b from falling below the supply voltage (VCC). The voltage across the capacitor 154a therefore cannot become more negative than the typical voltage drop across a conductive diode (about 0.5-0.7 Volts). This small negative voltage can be sustained by most piezoelectric elements.

If, in the same manner as before, the circuit is excited by the input signal 150 to resonate, the amplitude of the oscillating voltage across the piezoelectric element 22 (represented by capacitor 154a) can be made larger than the supply voltage (VCC), but the voltage cannot become negative. A similar statement holds true for the physical capacitor 154b so that a polar electrical component may be chosen there as well. Further, if the piezoelectric element has multiple piezoelectric layers and is electrically split so as to be represented as two capacitors 154a and 154b, the driver circuit of Figure 66 advantageously requires only a single control signal 150 to drive the piezoelectric element.

It has been observed that for a given voltage amplitude of the electric input signal to the piezoelectric element 22, the electrical current consumption of the piezoelectric element increases sharply for excitation frequencies just below certain resonance frequencies of the vibration element 26, and drops sharply just above those resonance frequencies. For rod-like vibration elements 26, these frequencies typically correspond to longitudinal modes. This electrical effect can be used to cheaply and quickly determine a particular vibration mode without using specialized measuring equipment such as a laser vibrometer. The sharp decrease in current just above a certain resonance frequency can be used to reduce the electrical power necessary to drive the vibratory unit 26 if the motor assembly 20 can be operated at these frequencies. Also, the electronics could be configured to automatically detect the drop in current and track the frequency at which the drop occurs, hence advantageously providing feedback. This feedback can be used to adapt the optimal operating frequency to changing external influences, such as temperature and humidity. Also, this kind of feedback can be used to detect the mechanical load that the motor must move.